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To cite this article: YM Khan *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1226** 012071

IOP Conf. Series: Materials Science and Engineering 1226 (2022) 012071 doi:10.1088/1757-899X/1226/1/012071

Hybrid-electric and hydrogen powertrain modelling for airplane performance analysis and sizing

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Abstract. This paper describes a framework for parametric modelling of hybrid-electric powertrain components for innovative airplane configurations. These models are used in scalability studies and performance analysis of novel propulsion architecture. The methodology involves culmination of these models in a set of tools specifically developed to study the initial and conceptual sizing of hybrid-electric aircraft. This allows quick parametric evaluation of various configurations based on components at different technology readiness levels, such as batteries and fuel cells. Characteristics and performance of the power-train components are evaluated using computational analysis as well as laboratory tests. This information is used to develop numerical models described in the paper and to validate the sizing of fundamental propulsion components. Applications to two variants of a commuter aircraft are given, one using a serial hybrid-electric architecture based on a thermal engine, and the other using a fuel-cell system fed by a gaseous hydrogen tank.

1. Introduction

Hybrid-Electric (HE) propulsion has recently emerged in the aerospace industry, buoyed by the pace of change in the automotive sector and by the need to transition towards more environmentally sustainable transportation means. Indeed, HE aerial vehicles promise several benefits [1, 2]: low- or zero-emission flight, the potential to open up new air transportation missions, the possibility of safer flight, and an enhanced design flexibility, enabled by Distributed Electric Propulsion (DEP) [3]. However, there are also some drawbacks hindering the trend to HE propulsion. Examples are low weight performance of energy storage devices, lack of regulation for future mobility concepts, and uncertainty on future market demand.

This study contributes to the H2020 MAHEPA project (Modular Approach to Hybrid Electric Propulsion Architecture), which aims to investigate and study HE propulsion potential to build-up a technological know-how and adopt a modular approach to design and run novel scalable HE powertrains. Particularly, the project includes the development and testing of two different hybrid-electric powertrains. One of the architectures employs an Internal Combustion Engine (ICE), while the other uses a hydrogen-fed Fuel Cell (FC) system as Power Generation System (PGS).

As part of MAHEPA project, methods capable of supporting the conceptual/preliminary design and analysis of HE aircraft have been developed [4,5]. These are remarkably different from traditional procedures for conventionally driven aircraft since the latter cannot be extended "as are" to hybrid-driven realizations. Such methods include tailor-designed parametric models for the powertrain components that will be fine-tuned with the experimental data collected in dedicated laboratory measurements, and the data coming from the flight test campaigns, carried out to assess component and system performance.

Once validated and established as a reliable, such framework is then extended to the study of passenger aircraft for regional applications, such as a 19-seat commuter aircraft. This methodology allows the preliminary sizing of a HE aircraft of arbitrary size, starting from mission requirements and other classical design specifications (such as certification requirements and operational constraints). As such, it contributes to scenario studies on the transition of passenger air transportation from hydrocarbon-based to HE propulsion [6–8].

Particularly, serial hybrid-electric aircraft are targeted, together with Pure-Electric (PE) aircraft, included as an extremal case in the serial-HE category. Furthermore, conventional (i.e., ICE-only powered) aircraft can also be considered, by tuning the input parameters to obtain a limit case of a HE aircraft without the electric component of the powertrain.

It is worth noting that modelling for preliminary sizing and for performance are mostly overlapping for two different reasons. Firstly, this allows to have coherent sizing/performance modules. Secondly, the use of detailed enough performance models during the design process can help underlining and highlighting possible design constraints linked to the working principles of the subcomponents that might lead to and incomplete or suboptimal design solution.

2. Models Integration, Refinement and Consolidation

Models for powertrain components developed within the framework this study have been extensively used in a wide variety of HE flying vehicles. As a by-product of such activity, these models have been refined and tuned up to the current level of stability. For the sake of clarity, usability, and completeness, the next paragraphs are devoted to the description of the current, most updated version of the models developed for each component of the HE powertrain which include battery, fuel cell, gaseous hydrogen tank, thermal engines, and electric motor/generator.

2.1. Battery

The battery is one of the most critical components to be sized and modelled, as it must safely feed electric motors and store energy for the full flight mission or important parts of the mission. Its inherent low mass-specific energy capability inevitably implies a significant effect on the overall aircraft sizing. A Battery Pack (BP) is usually formed by battery cells connected in series and/or parallel to achieve desired current and voltage levels. Multiple ways of modelling battery performance are found in the literature, at various levels of detail and use case scenario [9].

2.1.1. Electric Circuit Based Model. Electric circuit-based models are the most employed in engineering applications. Part of the power produced during the electrochemical reaction within a battery is lost in the process. A common way to model this behaviour is representing the battery as a lumped resistance and voltage source [10]. Both open circuit voltage and resistance depend heavily on the battery chemistry and on the battery State of Charge (SOC). Power is mainly lost due to ohmic, activation and concentration losses. Figure 1 shows the voltage curve of a Lithium-ion Battery (LIB) cell. The blue line represents the open circuit voltage, while the orange line is the resulting battery output voltage V including the voltage drop RI due the resistance. The maximum discharging/charging C-Rate depends on the battery SOC. There is no notional value of the SOC to be used in defining the nominal C-rate. The most common choices are 50% or 80% state of charge [11].

2.1.2. Energy-In-The-Box Models. An energy-in-the-box approach simplifies the dependency of open-circuit voltage on SOC, assuming a constant nominal value. Losses are accounted for with charging (η_c) and discharging efficiencies (η_d) and maximum charging/discharging C-Rates can be set.

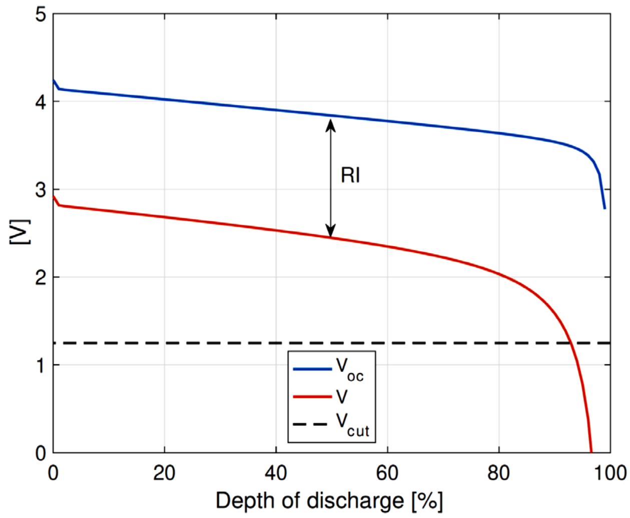

Figure 1: Discharge curve of a LIB cell. The battery voltage cannot drop below a certain cut-off voltage (dashed line), as it would damage the battery chemistry. This poses a clear limit to the maximum current I_{max} and therefore to the maximum C-Rate (defined as the ratio $\frac{I_{max}}{C}$, where C is the battery capacity in Ah). This effect is reversed when charging the battery: there is a limit on charging current, so as the battery peak voltage is not exceeded.

Although simplistic, this method is particularly suitable for aircraft preliminary sizing exercises where battery technology is often not yet defined and assumptions on the battery discharge curve cannot be made. For what concerns mass sizing, battery mass M_B depends on two parameters: the maximum battery power P_{Bmax} and the battery stored energy E_B. To represent this interaction, M_B is given by:

$$M_B \geq \max\left(\frac{P_{Bmax}}{p_B}, \frac{E_B}{e_B}\right) \tag{1}$$

2.2. Fuel Cell

The most suitable FC type for transport applications is the Proton Exchange Membrane (PEM). In this FC type, gaseous Hydrogen is used along with the compressed air necessary for the redox reaction to occur. The proposed modelling of the FC system is based on its inner physics and specifically on the polarization curve that relates current density input i to the voltage output V [12]. The other common type of fuel cell is the Solid Oxide Fuel Cell (SOFC), which operates at high temperatures (800-1,000°C) and is often used for stationary applications. SOFCs also suffer from slow start up time, heavier weight and fragile nature which make them unsuitable for transport applications [13,14].

2.2.1. Fuel Cell Sizing. A Fuel Cell Module (FCM) is composed of several elementary cells connected to achieve the required power, which is the product cell voltage and the current through it. By connecting the cells in series, the voltage of each cell adds up, and a new sub-system, called stack, is obtained. Similarly, by connecting multiple stacks in parallel, the total current is the sum of the current flowing in each stack. Multiple design choices arise when it comes to sizing the FCM as shown in Figure 2.

2.3. Gaseous Hydrogen Tank

According to the relevant classification, Type III and Type IV vessels are commonly used for the storage of hydrogen gas. Type IV tanks manage to halve the overall volume of the tank by increasing the pressure to 70 MPa as compared to a Type III tank. These vessels are made of a composite wound around a polymer liner. Type IV pressure vessels are the considered tank type for gaseous hydrogen in aeronautical applications. The mass M_t of gaseous hydrogen tanks can be retrieved using the tank gravimetric index μ_g and knowing the mass of hydrogen M_{H_2} that must be stored based on the mission profile sizing loops. The gravimetric index is defined as:

$$\mu_g = \frac{M_{H_2}}{M_{H_2} + M_t} \tag{2}$$

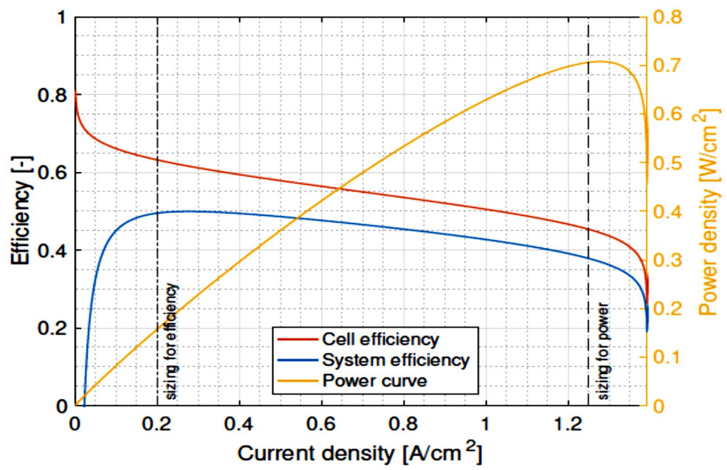

Figure 2: Example of FC efficiency and polarization curve with the sizing points for power and efficiency**.** If the maximum point is selected on the power curve, then the polarization curve enters in a steep slope region beyond current density of 1.2. Similarly, if the point of maximum efficiency is selected, the FC cannot supply max power, hence, the fuel cell ends up being oversized.

The volume of a certain mass of hydrogen M_{H_2} is obtained by knowing the operating pressure $\mathcal{P} = 70$ MPa and temperature $T = 357$ K, making it possible to estimate volume of hydrogen within the tank V_{H_2}. Provisions for an onboard thermal management system are not required within the operating temperature range of passenger aircraft [15,16].

2.4. *Thermal Engines*

Thermal engines are mostly employed as part of the PGS within Thermal Hybrid Electric airplanes. For the sake of aircraft preliminary sizing, it is necessary to derive appropriate and reliable surrogate models to estimate the Brake-Specific Fuel Consumption (BSFC) of thermal engines to accurately estimate fuel needs. Another important aspect of thermal engines is the decrease of maximum power with altitude that inevitably impacts the correct sizing of the engine. For the present purposes, two types of thermal engines were considered, turboshaft engines and reciprocating engines. For the turboshaft model, a reference BSFC map as a function of the flight Mach number M, altitude z and throttle δ was derived from Thrust-Specific Fuel Consumption maps in the appendices of [17] and shown in Figure 3.

Reciprocating engines for aeronautical applications have usually featured a large displacement and very low RPM, to increase reliability and reduce mechanical stress on the engine. For reciprocating engine, maps of fuel consumption are presented in Figure 4.

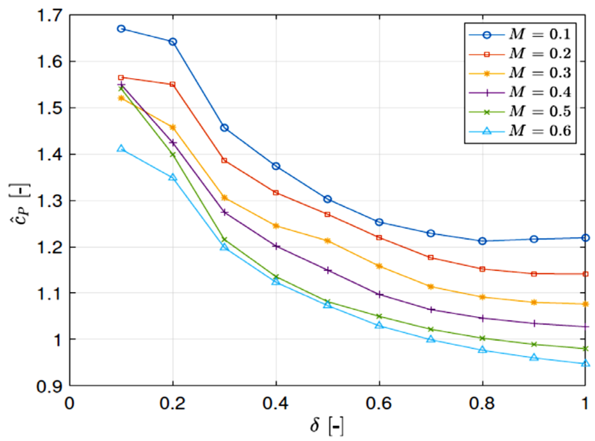

Figure 3: Map of normalised BSFC $\hat{c}_P$ as a function of Mach number M and throttle δ for a representative turboshaft engine at 8,000 ft.

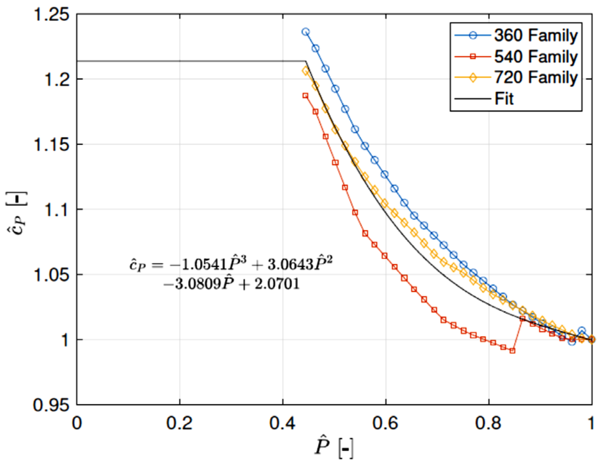

Figure 4: Map of normalised BSFC as a function of fraction of rated power for low-RPM reciprocating engine.

2.5. Electric Motor and Generator

Electric Motors (EMs) are easier to operate and maintain thanks to the lower number of moving parts and are less exposed to component failures than Thermal Engines. EMs normally work within a lower temperature range, and a warm-up process is not needed for this purpose. By design, an electric motor can serve as an electric generator receiving external mechanical power. Brushless DC and AC induction motors are extensively used in hybrid vehicle applications. The EMs are modelled using the 'Rubber motor' technique which starts from the map of a real EM and a loss model. A map of EM efficiency as a function of normalized torque and normalized rotational speed is generated [18]. Selecting the desired optimal efficiency, torque, and rotational speed the model can be customised to any application. Following this procedure, it has been reported in [18] that for 75% of the working conditions EM efficiency is greater or equal to 90% of the maximum efficiency.

3. Integration of Results from Laboratory Testing

Various models of the hybrid-electric drivetrain components presented in the previous sections were validated and fine-tuned with the experimental data. This data was obtained from the laboratory tests performed by the appointed consortium members of MAHEPA. Those results are being omitted for the sake of brevity in this paper. But the incorporation of laboratory results in the initial sizing suite led to the improved modelling capabilities of software tools which include HYPERION, ARGOS, and TITAN [4,5].

4. Case Studies

The availability of proficient sizing tools made it possible to evaluate various hybrid-electric configurations on a broad scale of future technological advancements. Regarding the propulsion configuration, two distinct propulsion architectures are presented in this paper, namely, Thermal Hybrid Electric (THE) and Hydrogen Fuel Cell (HFC). In case of THE, a thermal engine (typically, an ICE) is used to recharge onboard batteries and use them based on an efficient charging/discharging strategy. While the second propulsion architecture, HFC, uses a fuel cell to provide power to EMs with propellers and to recharge the onboard batteries. Similarly, an optimized BP usage strategy is implemented to fully exploit this innovative setup.

Apart from the propulsion configurations, future technological developments of some of the key components have been considered to design and size an aircraft with low chemical and noise emissions. In general, contemporary, near future and long-term predictions about the performance of the batteries and fuel cells have been explored. The starting point of these case study is the year 2020 which represents the current state of the art for propulsion components. While the year 2035 and the year 2050 represent the near future and long-term time scale. Once again, for the sake of brevity the performance predictions for only 2050 are presented here in Table 1.

Finally, two aircraft categories based on passenger capacity were evaluated on the criteria mentioned above. These include a 19-seater (A19) aircraft complying to CS-23 requirements and a second aircraft with a capacity of 70 seats (A70) complying to CS-25 requirements in general. In this paper, we only present results of the 19-seater hybrid electric aircraft keeping the mission requirements of the Dornier 228 as presented in Table 2.

Table 1. Technology assumptions for 2050.

Parameter	Numerical Value and Units
BP Specific Power	5,070 W/kg
BP Specific Energy	1,690 Wh/kg
EM Specific Power	16,450 W/kg
FCS specific power	8,800 W/kg

Table 2. General design requirements for 19-seater aircraft.

Requirements	Numerical Value and Units
Range	400 km
Loiter time	35 min
Transition altitude	1,400 ft

5. Results and Discussion

The results from the initial sizing tool HYPERION are discussed here based on the premise of case studies outlined in the previous section. The comparison between various option is based on the results of mass breakdown, energy, and power time histories and finally the sizing matrix plot SMP. Figure 5 shows the mass breakdown of A19THE and the maximum takeoff mass (MTOM) of 6,812 kg which is relatively higher than the existing Do-228 powered by the conventional turboprop aircraft. Although battery mass is significant here, but the fuel mass is reduced to nearly half of that required for Do-228 (about 500 kg) which directly translate into lower chemical emissions.

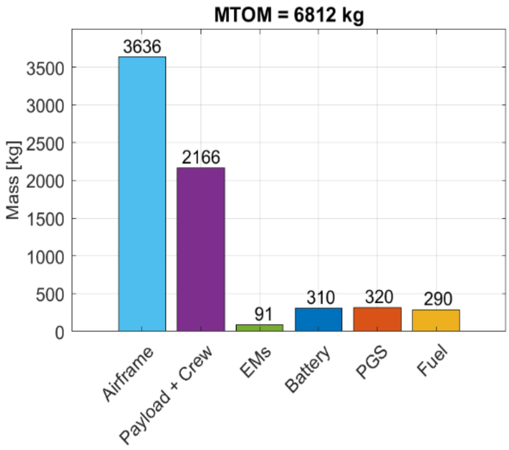

Figure 5: Mass breakdown for A19THE.

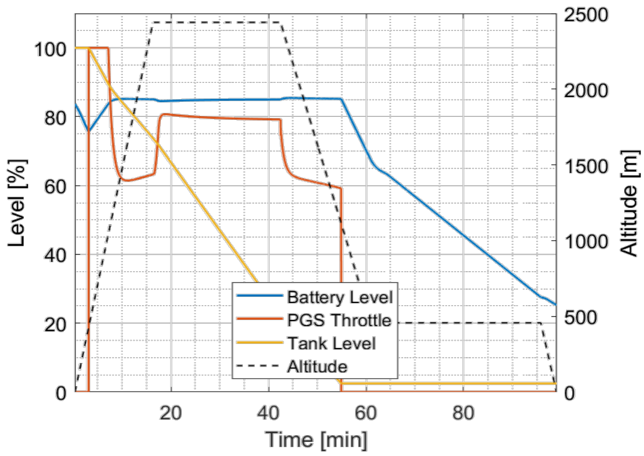

Figure 6: Energy time histories for A19THE.

Despite the 8-times improvement in 2050 estimates of BP specific capacity as compared to state of the art in 2020 and 3-times improvement in BP specific power, the aircraft is still heavier than its conventional counterpart. But the real advantage is the reduced emissions both chemical and noise. For example, Figure 6 shows the energy usage time histories plotted against the altitude profile: it is evident that the takeoff and initial climb can be carried out using battery power alone which results in lower noise emission levels much to the respite of neighbouring communities around the airport. Later during the flight, after reaching a transition altitude as mentioned in Table 2, thermal engine can be switched on to the charge the onboard batteries.

As far as FC-powered aircraft is concerned, the results of the case study look promising and show a clear decrease in the MTOM of the aircraft. This is evident in Figure 7 where the MTOM for this type of aircraft is 5,941 kg which is about 8% lower than the current technology Do-228 and 13% lighter than the A19THE version. The PGS throttle line in Figure 8 represent the hydrogen release valve from the storage to the FC which is dependent on the power requested during the various phases of the mission. It is worth mentioning at this point that the battery is not allowed to discharge below 25% SOC which enhances the battery life and flight safety by preserving energy for any crucial go-around due to unforeseen event. However, for the planned decent and diversion procedure battery is kept at the maximum allowable level which is set to 80% SOC for reasons pertaining to long term battery health.

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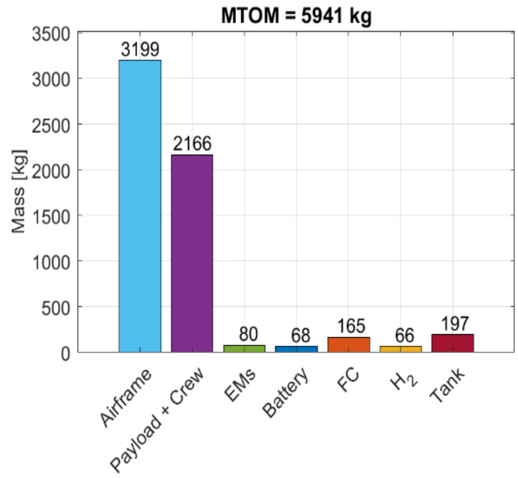

Figure 7: Mass breakdown for A19GH2.

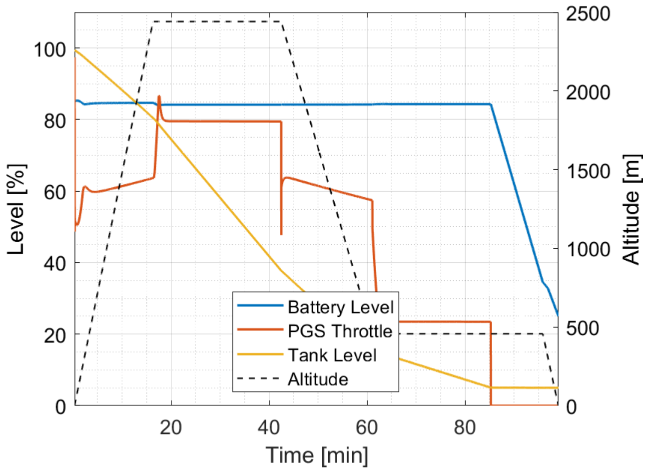

Figure 8: Energy time histories for A19GH2.

The results from initial sizing tool HYPERION are incorporated with a preliminary design tool called TITAN. The starting point for this iterative process is the Sizing Matrix Plot (SMP) as shown in Figure 9. The process culminates in a weight-optimal preliminary design down to the component level sizing and placement as shown in Figure 10. The basis of these advanced preliminary sizing tools lies in the modelling scheme presented in this paper.

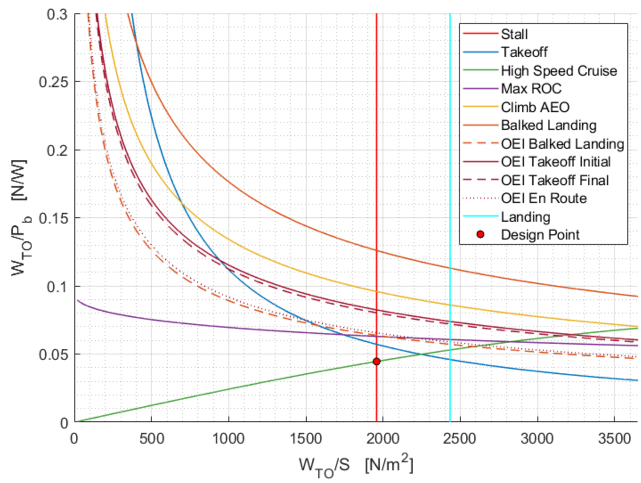

Figure 9: SMP indicating performance constraints and the design point.

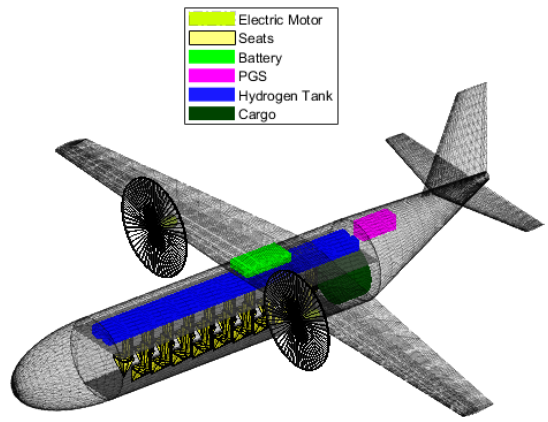

Figure 10: Preliminary design and the component placement for A19GH2.

6. Conclusion

The modelling techniques presented above provide a fast, accurate and reliable way to assess and perform scenario studies for HE aircraft. Results of these studies can contribute to the definition of a road map to adopt these new propulsion architectures in the future. In the presented applications, the HFC propulsion shows a distinct advantage, not only over the current 19-seater conventional aircraft but also proves more weight-efficient than that THE version. However, HFC technology is still in its infancy as far aerial transport applications are concerned. Therefore, THE presents a reliable and proven transitional alternative while waiting for the HFC technology to mature. In addition, as EM-driven propeller aircraft exhibit architecture commonality between THE and HFC, clean-sheet THE designs can be pursued for transport applications which can later be retrofitted with an HFC PGS.

7. Funding

This research was partially funded by the EU Horizon 2020 research and innovation program, under project MAHEPA, GA N. 723368.

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